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SIMULATION OF DYNAMICS OF MOVING MAGNET LINEAR ACTUATOR

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ABSTRACT

The paper presents simulation of the dynamics of recently developed permanent magnet linear actuator for individual needle driving in knitting machines. The dynamics is simulated using the electric circuit – mechanical motion system of equations with obtaining the necessary functions from 3D magnetic field analysis of the actuator. Results for the coil current, mover displacement and velocity and of the electromagnetic force are obtained.

Index Terms – Linear actuators, moving magnet, dynamic characteristics, finite element method.

1. INTRODUCTION

Permanent magnet linear actuators have been increasingly employed in recent years [1], [2] due to their advantages over the actuators with neutral electromagnets.

A novel trend in knitting machines is individual driving of each needle, which allows increased performance with respect to traditional knitting machines with common driving of the needles. In a previous paper [3], the static force characteristics of recently developed permanent magnet linear actuator for individual needle driving is studied using three-dimensional finite element analysis.

In the present paper, an approach for simulation of dynamics of the actuator is presented.

2. ACTUATOR CONSTRUCTION

The principal construction of the actuator is shown in Fig. 1. The actuator consists of two cores, each with several teeth placed on a common yoke. There is a coil placed on each tooth. The mover is brick-type rare earth permanent magnet magnetized in transversal direction. The specific requirement to the actuator is that the mover has to be able to stay at four stable positions when there is no supply to the coils.

The principle of operation of the actuator is such that at each position during the motion of the mover, several coil couples are supplied with voltages of suitable polarity. The number of the coils and the polarities of the voltage supplies depend on the position of the mover. Thus the force acting on the moving permanent magnet is in the desired direction.

The actuator features increased energy efficiency with respect to other actuators that use electric power in order to keep the mover at a desired position. It utilizes electric power only during the motion of the mover from one to another position. The mover is kept in each of the fixed positions without power supply, due only to the holding force of the magnet.

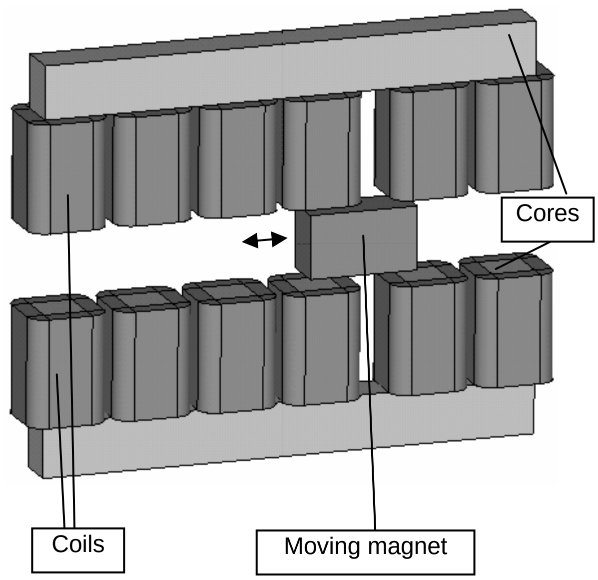

Figure 1 Principal construction of the actuator

The section of each tooth is 4×4 mm, its height is 10 mm. The section of the yoke in *y-z* plane is 4×5 mm. The dimensions of the permanent magnet (x×y×z) are *8*×4×6 mm. The distance between each two adjacent teeth axes is 8 mm, only between the 4th and the 5th it is 10 mm.

A schematic of the electrical connection of the coils is presented in Fig. 2. The coils of the actuator are connected in series and R1=R2=3=R is the active resistance of the copper wire of the windings.

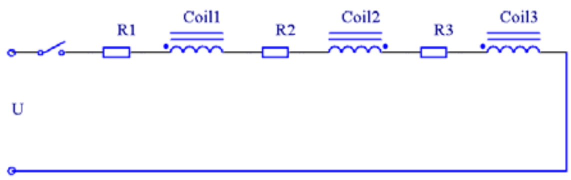

Figure 2 Electrical connection of the coils of the actuator

The study is carried out for one stage of the magnet motion, which employs power supply of three coil couples – the first three from left to right in Fig. 1. The stroke of this stage is 8 mm. The coils are connected in series. In this way, the current in each coil is the same and the results from the magnetostatic field modelling with constant coil m.m.f. can be used for obtaining the necessary functions for the dynamic modelling.

3. SIMULATION OF THE DYNAMICS

The equation for the above circuit can be written as

$$U = 3\ R\ i(t) + \frac{d\psi_1}{dt} + \frac{d\psi_2}{dt} + \frac{d\psi_3}{dt}\,. \tag{1}$$

Here, *i(t)* is the current flowing trough all tree coils, U is the supply voltage and ψ_1, ψ_2, ψ_3 are flux linkages for each of the coils.

The flux linkage, in steady state, can be considered to be dependent only on the current through the coils and the position x of the permanent magnet in the armature. In this case the above equation can be rewritten as:

$$\begin{aligned} U &= 3Ri + \left(\frac{\partial\Psi_1}{\partial x} + \frac{\partial\Psi_2}{\partial x} + \frac{\partial\Psi_3}{\partial x}\right)v + \\ &+ \left(\frac{\partial\Psi_1}{\partial i} + \frac{\partial\Psi_2}{\partial i} + \frac{\partial\Psi_3}{\partial i}\right)\frac{di}{dt} \end{aligned} \tag{2}$$

The forces acting along the moving axis of the armature are the electromagnetic force and friction forces counteracting against the direction of movement. The latter are taken into account by the expression:

$$F_v = \beta v\,, \tag{3}$$

where v is the velocity of the armature and β is the damping coefficient.

The electromagnetic force *Fmag* is present not only when the coils are energized but also with zero current due to the flux of the permanent magnet, passing through the core. At steady state it depends on the position of the permanent magnet – x and the current i.

The equation of the force balance can be written as

$$m\frac{dv}{dt} = Fmag - F_v\,. \tag{4}$$

Here, m is the mass of the armature.

One more equation is needed in order to obtain the system describing the dynamics. It is the relationship between the displacement and the velocity

$$v = \frac{dx}{dt}\,. \tag{5}$$

Thus the system of ordinary differential equations becomes

$$\begin{cases} \dfrac{dx}{dt} = v \\ \dfrac{dv}{dt} = \dfrac{1}{m}\left(Fmag - \beta v\right) \\ \dfrac{di}{dt} = \dfrac{U - 3Ri - \left(\dfrac{\partial\Psi_1}{\partial x} + \dfrac{\partial\Psi_2}{\partial x} + \dfrac{\partial\Psi_3}{\partial x}\right)v}{\left(\dfrac{\partial\Psi_1}{\partial i} + \dfrac{\partial\Psi_2}{\partial i} + \dfrac{\partial\Psi_3}{\partial i}\right)} \end{cases} \tag{6}$$

For the solution of (6) essential role plays proper definition of the electromagnetic force and the partial derivatives of the flux linkages. All they are functions of the current and of the displacement of the magnet.

In order to obtain these functions, first a series of finite element analyses of the magnetic field is performed by varying both current and the displacement (magnet position).

Three-dimensional finite element method employing magnetic scalar potential formulation is used. For the finite analysis the program ANSYS® [4] is used. Tetrahedral finite elements are employed. An example of the finite element mesh is shown in Fig. 3.

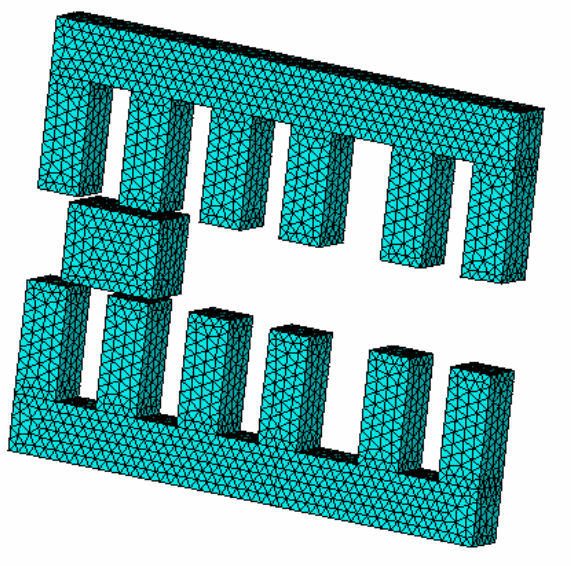

Figure 3 Finite element mesh

From each finite element analysis the results for the electromagnetic force and the flux linkages of the coils are obtained. Having these results for the whole ranges of the possible values of the current and the displacement, bicubic spline approximations are created for the electromagnetic force and the three flux linkages as functions of the displacement and the current. These approximations give also the functions of the partial derivatives present in (6).

4. RESULTS FROM THE SIMULATION

Results are obtained for the time variations of the magnet displacement and velocity, current in the coils and electromagnetic force. In Fig. 4, the displacement of the mover (armature) is given.

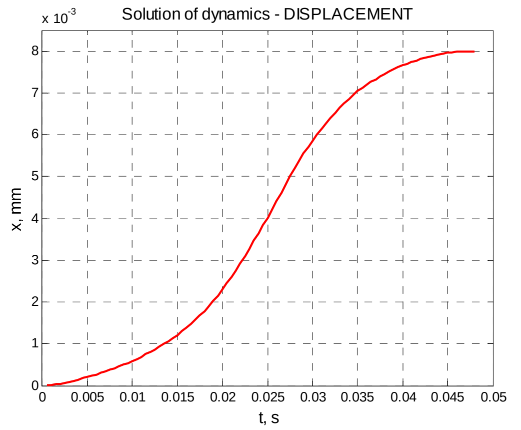

Figure 4 Displacement of the armature vs. time

As there is no opposite force in the beginning, the motion practically starts immediately.

In Fig. 5, the coil current waveform is shown. This curve is determined by the shape of the magnetic core, where the cogging force is significant.

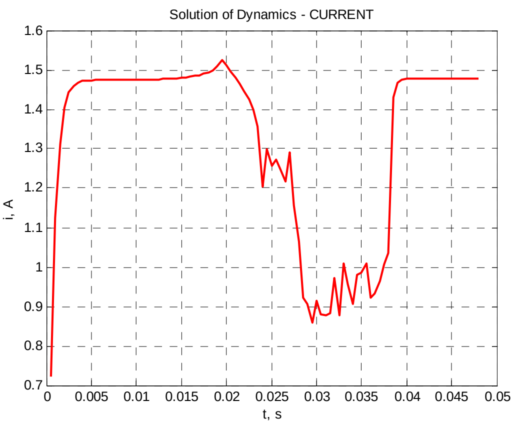

Figure 5 Current in the coils vs. time

The mover velocity is shown in Fig. 6. It exhibits a maximum about the middle of the studied time period and the decreases to zero. The studied final position is one of the stable magnet positions that do not need power supply in the coils to stay at. For further motion the coil supply is to be changed.

In Fig. 7, electromagnetic force in time is given. It has in fact similar behaviour to the one of the velocity. For displacements after the final one for this study (8 mm), the force becomes negative. This ensures stable final position of the mover. This position will also be kept after switching off the power supply as the permanent magnet will keep it.

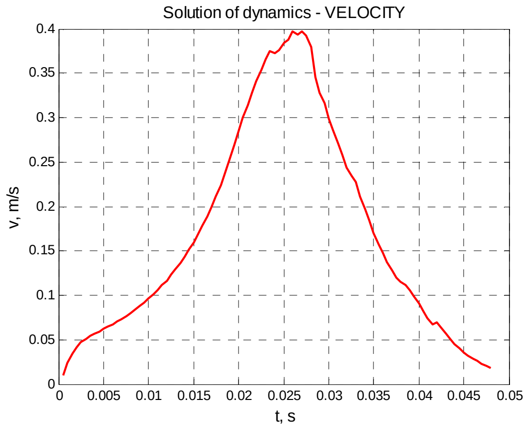

Figure 6 The velocity of the armature.

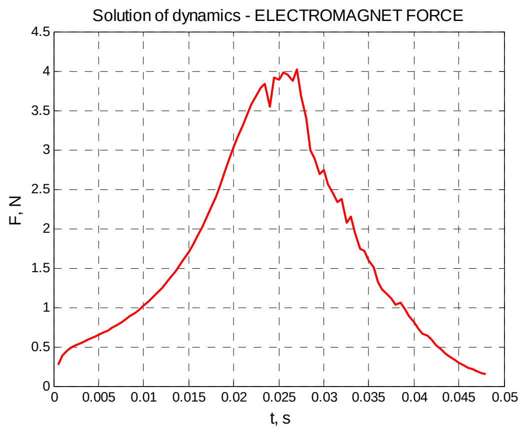

Figure 7 Electromagnetic force

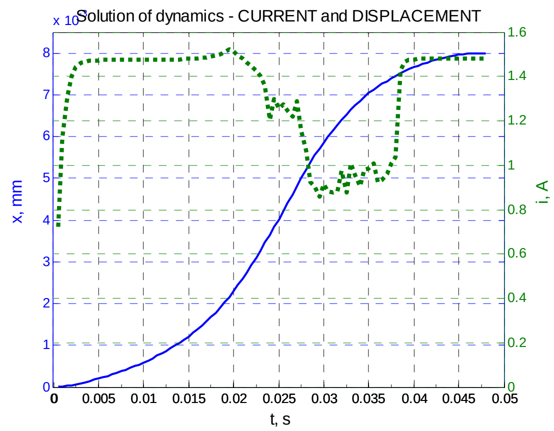

Figure 8 The displacement and the current during the motion

5. CONCLUSIONS

The presented simulation of the dynamics of linear actuator with moving permanent magnet shows the way of mover behaviour during one stage of its motion. This study gives the opportunity for further development of the control strategy of the actuator.

Acknowledgments

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